Firn aquifer study near Helheim Glacier based on geophysical methods and in situ measurements

Clément Miège
Richard Forster
Olivia Miller
Kip Solomon

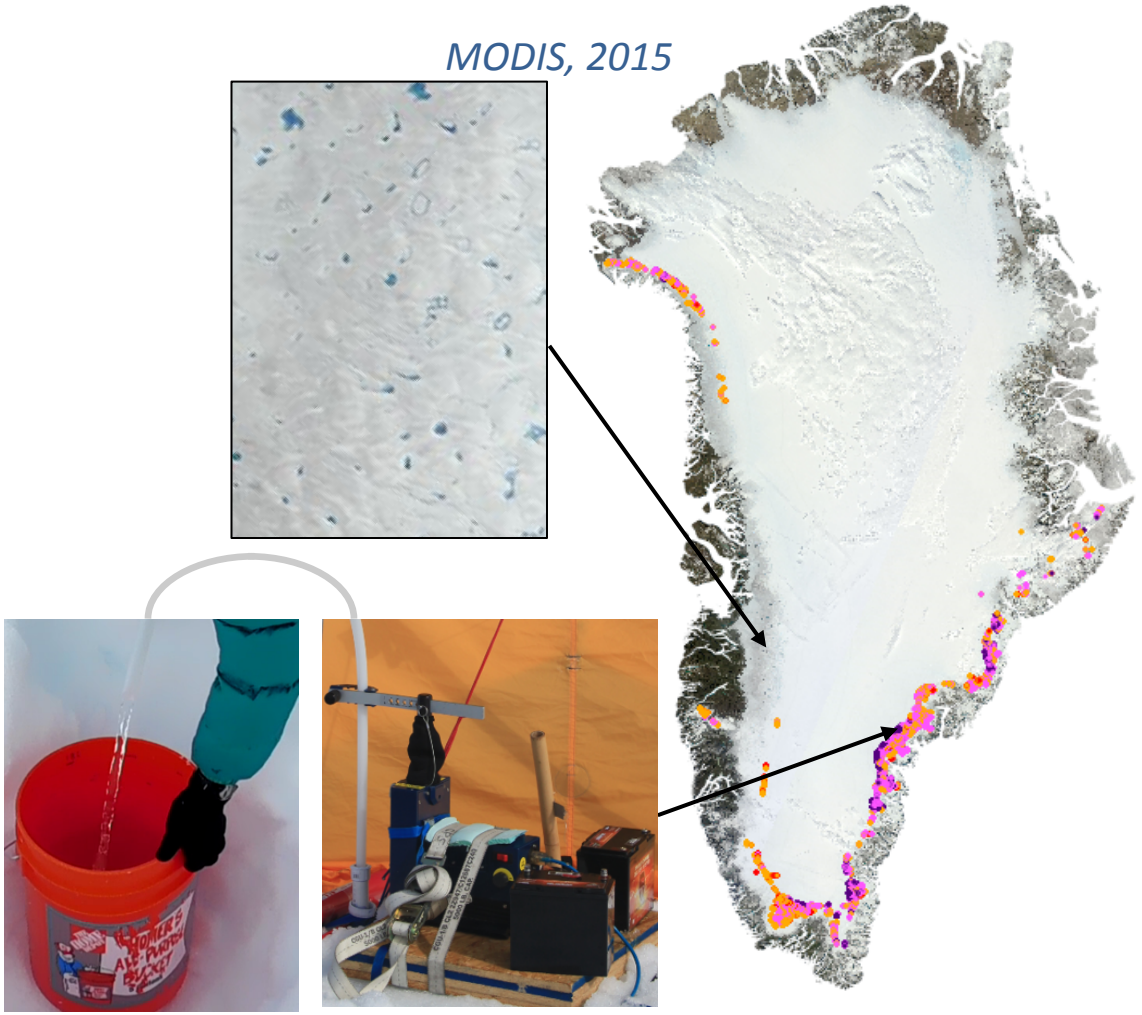
Lora Koenig

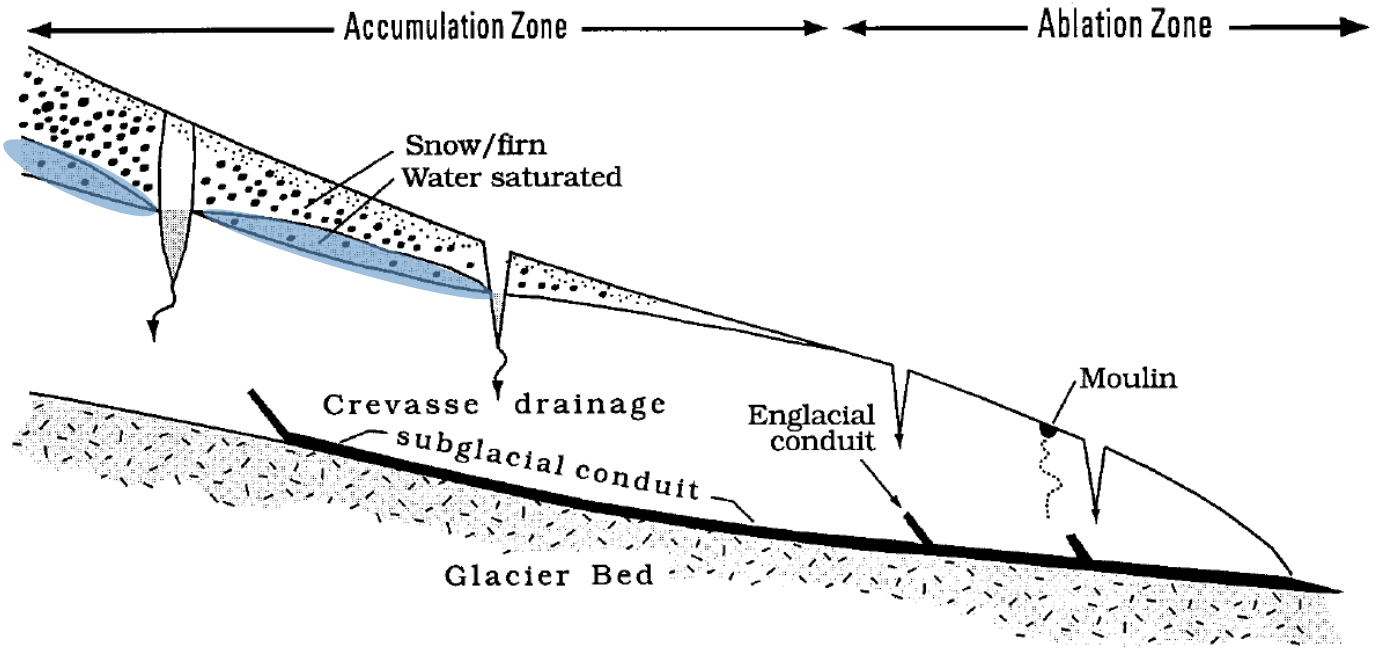
Anatoly Legchenko

Nicholas Schmerr
Lynn Montgomery

Ludovic Brucker

Prasad Gogineni
John Paden





Fountain and Walder, 1998

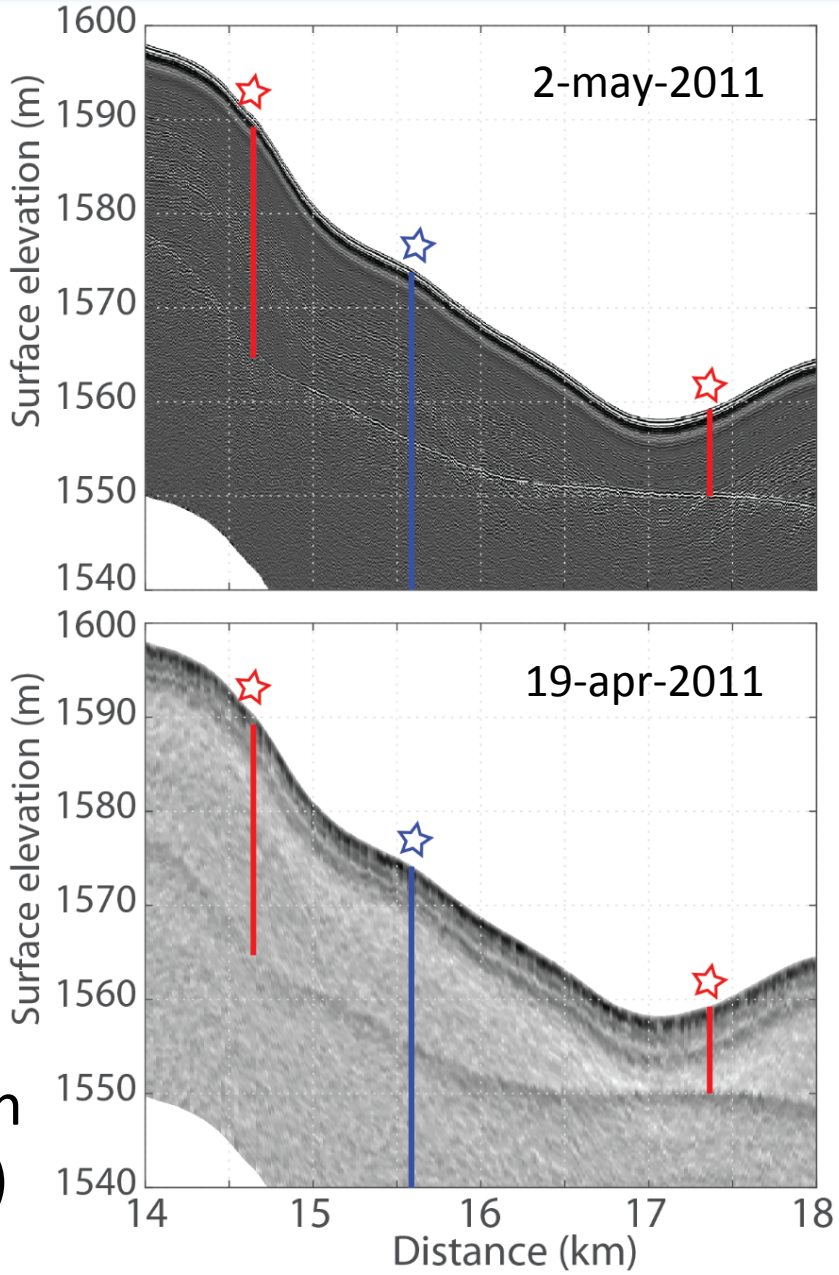
Firn aquifers:

- develop at depth above the firn/ice transition
- sensitive to surface melt variations
- store meltwater and delay runoff
- are seasonal to multi-year features

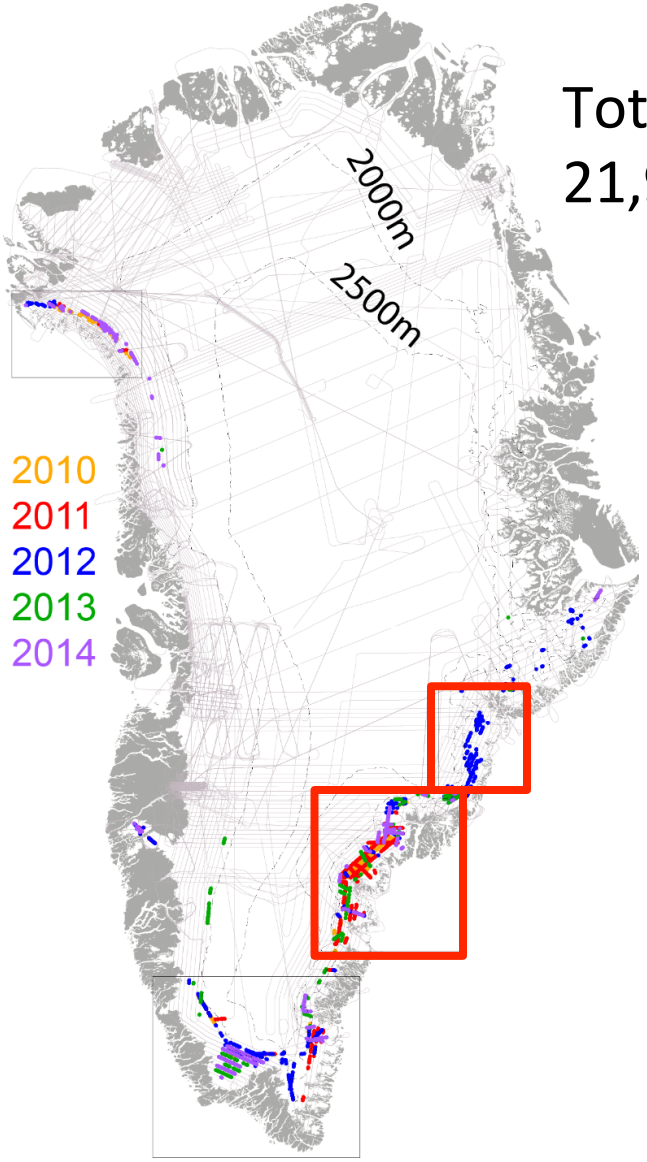
Greenland firn aquifer detections:

GSSI ground radar (400 MHz)

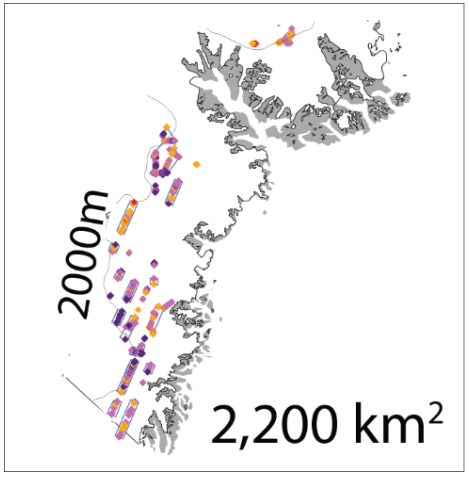
OIB Accumulation Radar (750 MHz)



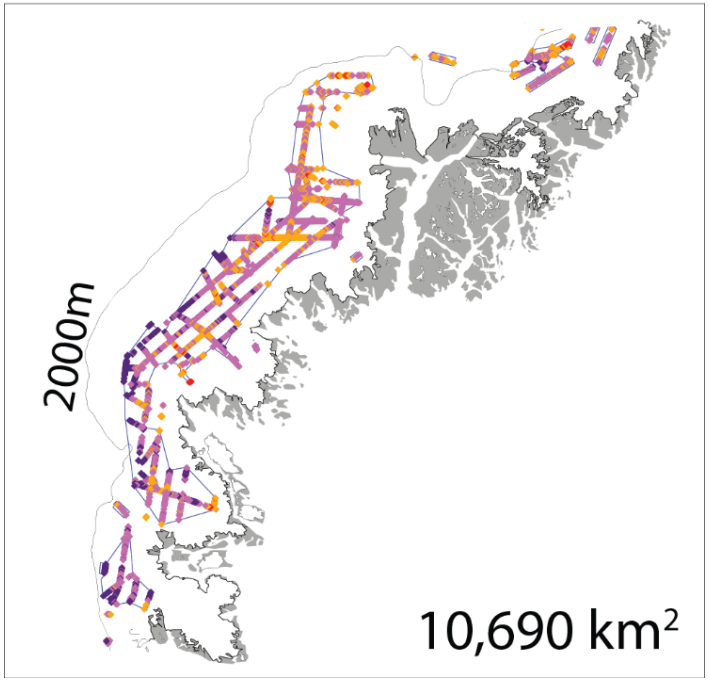
OIB with Accumulation Radar onboard allows precise detection of firn aquifers



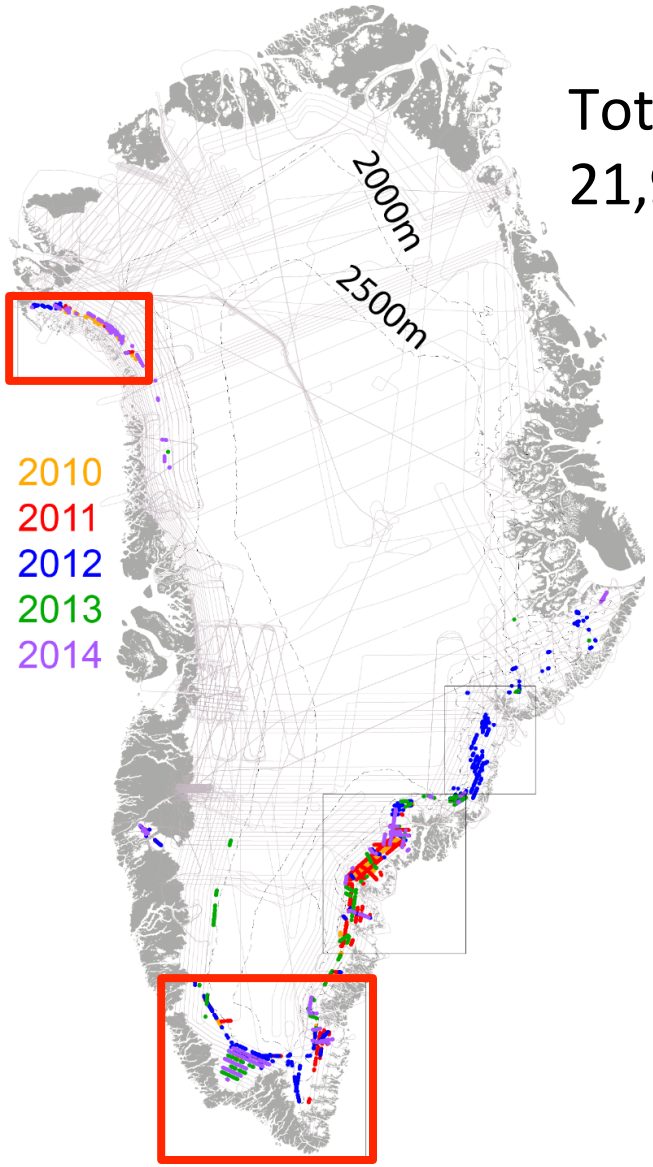
Total area:
21,900 km²



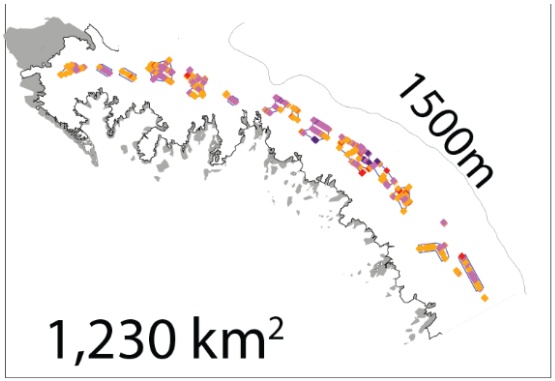
Depth to water (m)
- 5 - 10
- 10 - 20
- 20 - 30
- 30 - 40

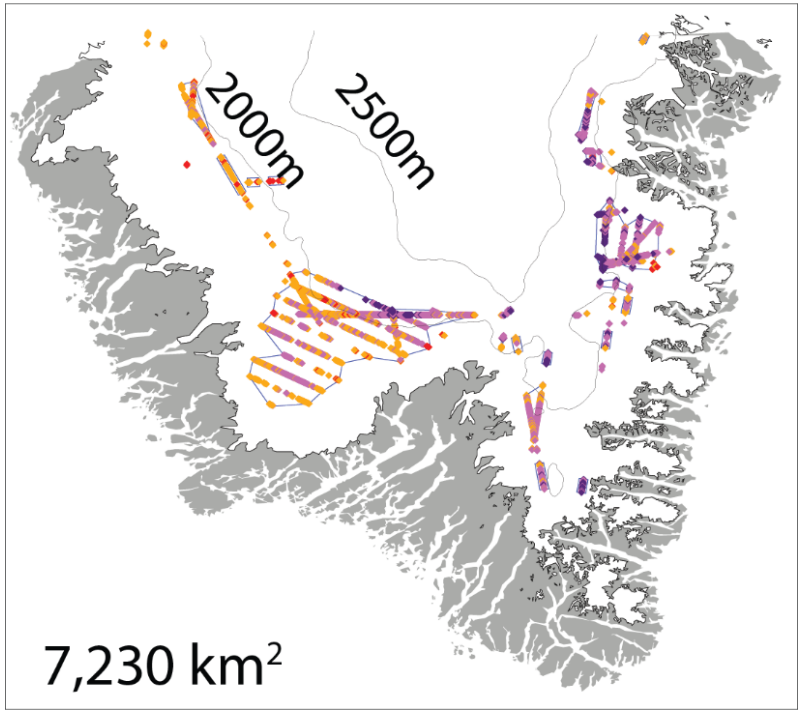


OIB with Accumulation Radar onboard allows precise detection of firn aquifers



Total area:
21,900 km²



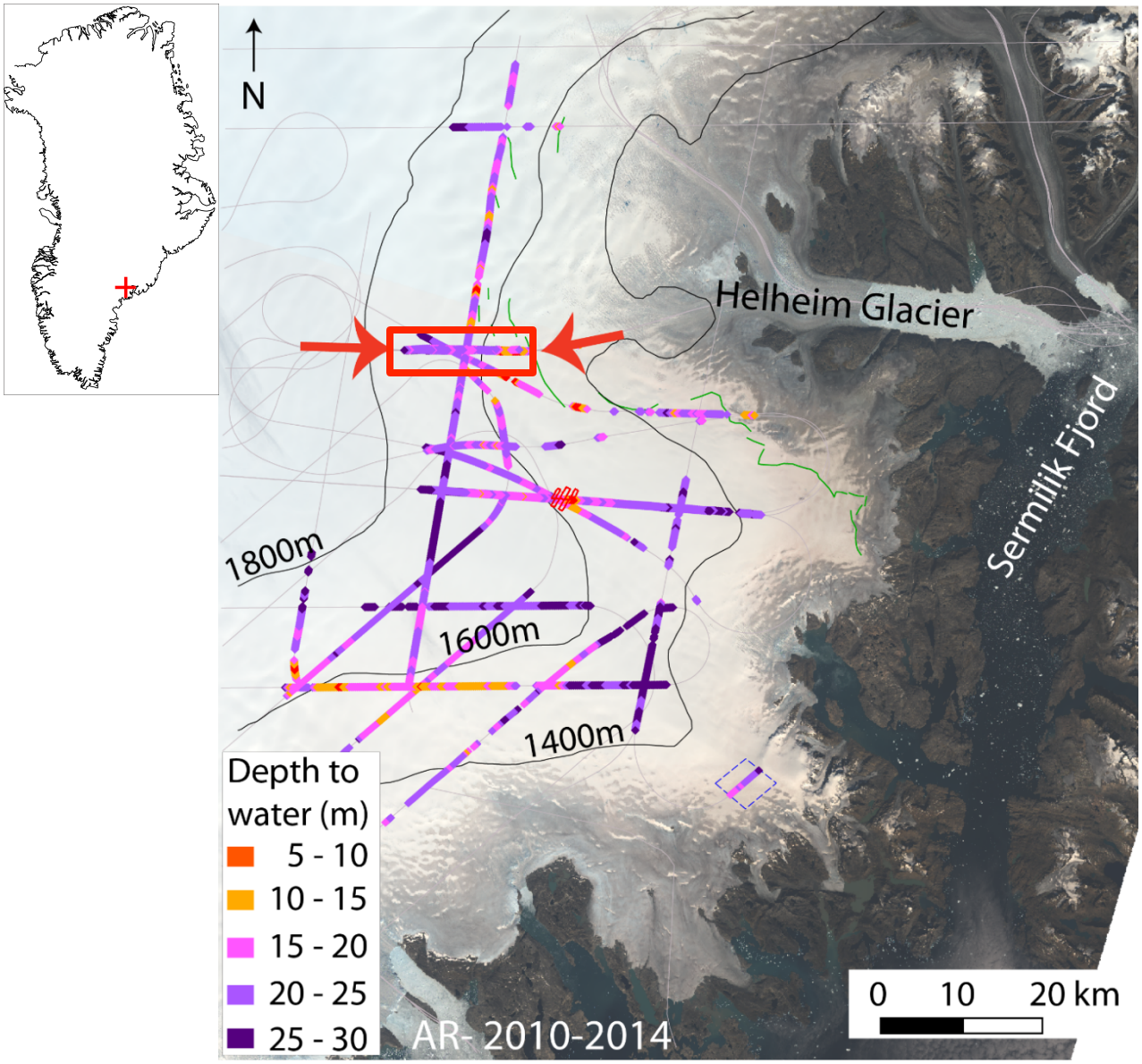


Objectives of this study:

- Characterize firn aquifer evolution for the last 2 decades
- Constrain aquifer water volume
  and its variations in space and time
- Determine water residence time
  and flow rate through the aquifer
- Identify pathways, connections
  and water contribution to englacial hydrology

Study site:

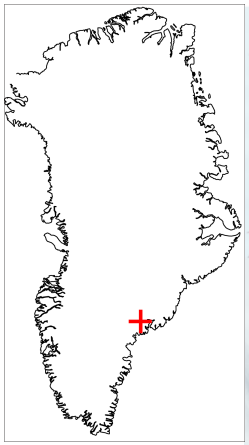
Upstream of Helheim Glacier, SE Greenland

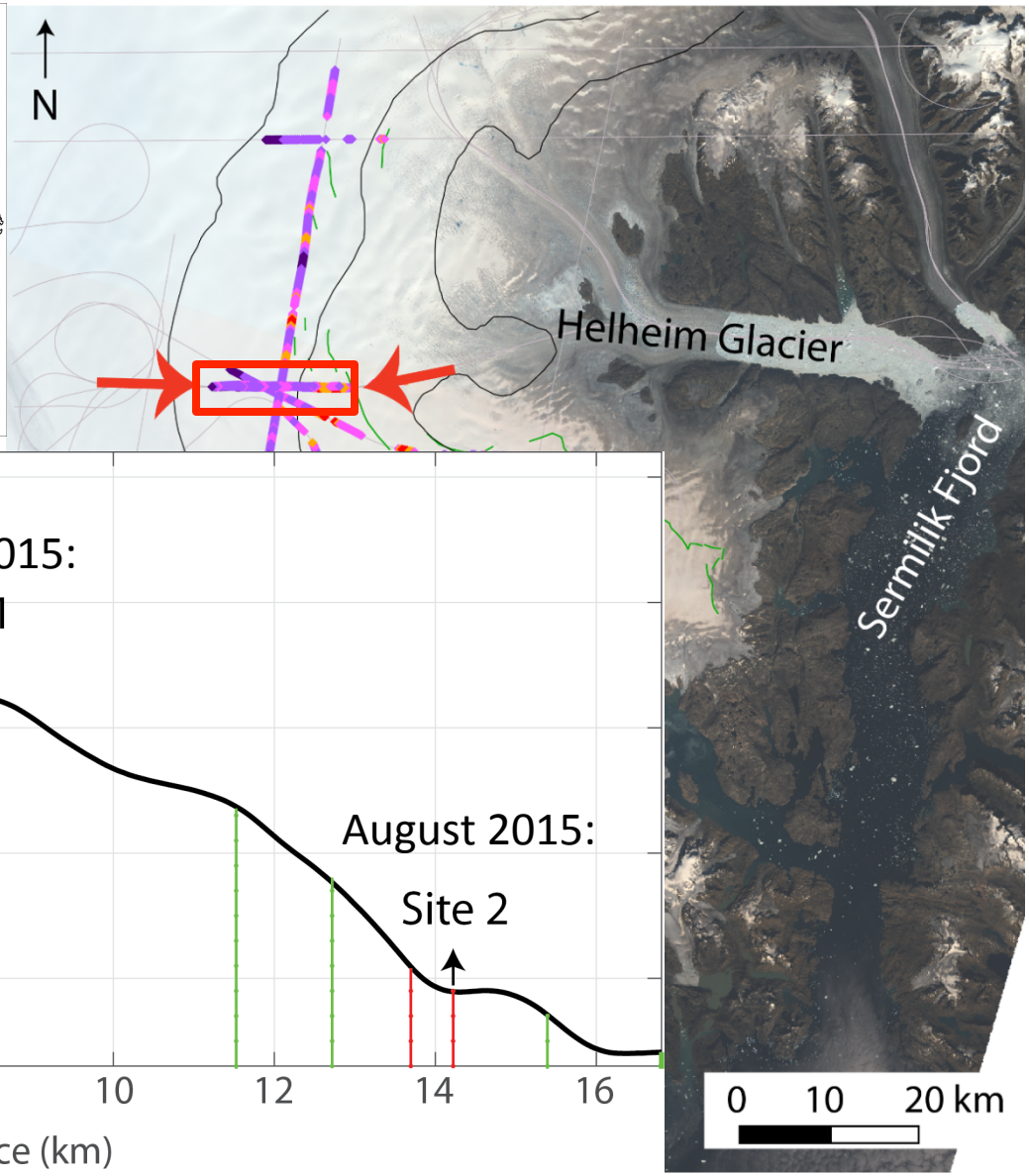


Background: Landsat 8 (USGS)

Study site:

Upstream of Helheim Glacier, SE Greenland





Background: Landsat 8 (USGS)

Geophysical investigations:

- Ground and OIB radars

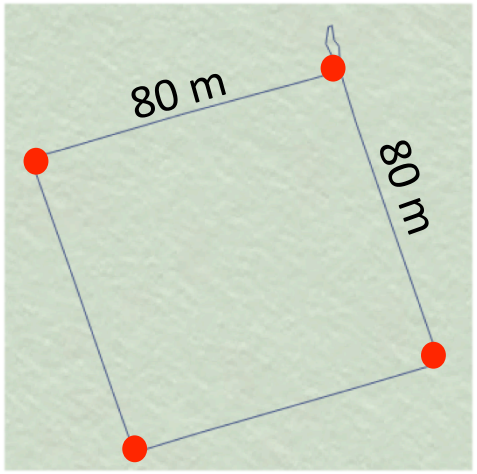
Objectives:

- aquifer extent mapping
- aquifer temporal progression
- water-table elevation changes
- relate to volume changes

Geophysical investigations:

- Ground and OIB radars

- Magnetic resonance soundings (MRS) (LTHE, Grenoble)



Worldview image (DigitalGlobe©)

Photo: L. Montgomery

Objectives:

- aquifer extent mapping
- aquifer temporal progression
- water-table elevation changes
- relate to volume changes

Objective:

- Integrated water volume to 40 m

Geophysical investigations:

- Ground and OIB radars
- Magnetic resonance soundings
- Seismic refraction (Univ. Maryland)

Survey line:

Objectives:

- Vertical stratigraphy
- Velocity structure -> variations in water volume through the aquifer

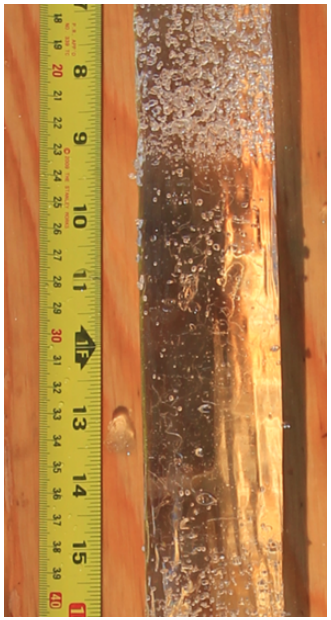
Geophysical investigations:
- Ground and OIB radars
- MR soundings
- Seismic refraction

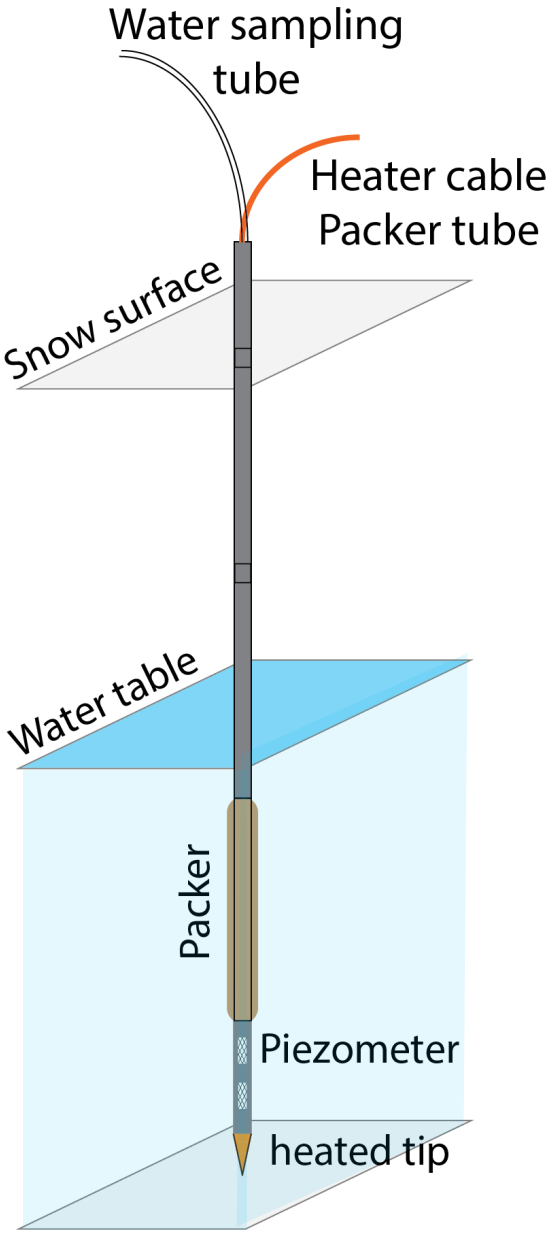
In situ measurements:
- Firn/ice densities
- Hydraulic conductivities
- Water dating (CFCs, Tritium, noble gases)

Objectives:
- Vertical structure
- Water age
- Water residence time
- Flow rates

Saturated firn (within aquifer ~20 m)

Clear ice layers (below aquifer ~ 35 m)

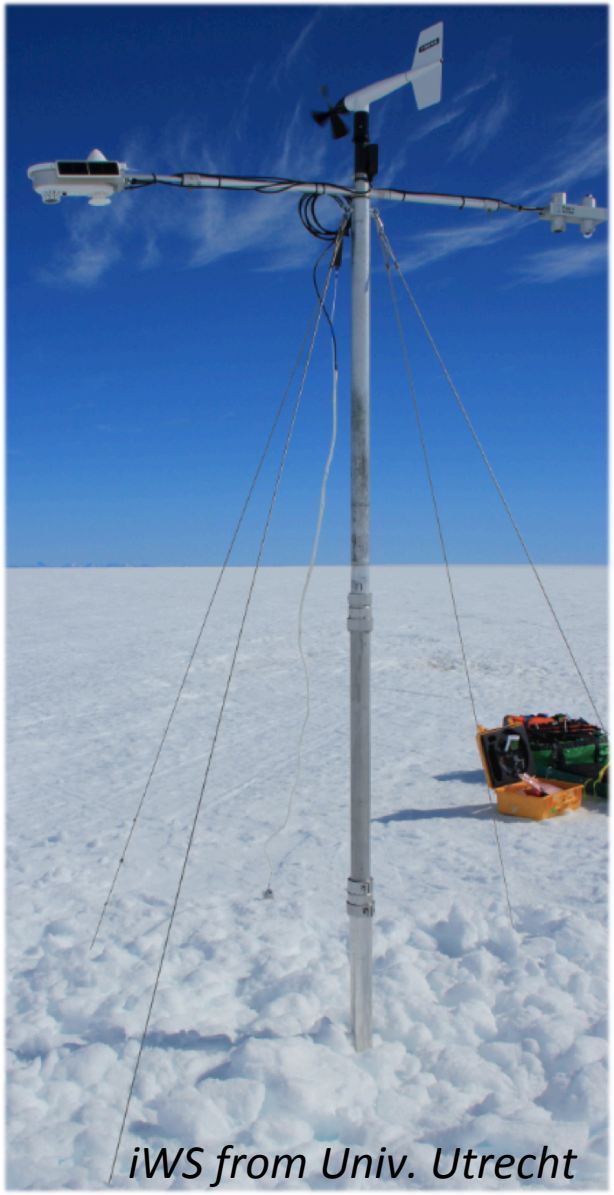




Geophysical investigations:
- Ground and OIB radars
- MR soundings
- Seismic refraction

In situ measurements:
- Firn/ice core extraction
- Hydraulic conductivities
- Water dating

Monitoring:
- Firn and air temperatures
- Water level changes
- Compaction rates (Univ. Colorado)
- Energy balance (Univ. Utrecht)

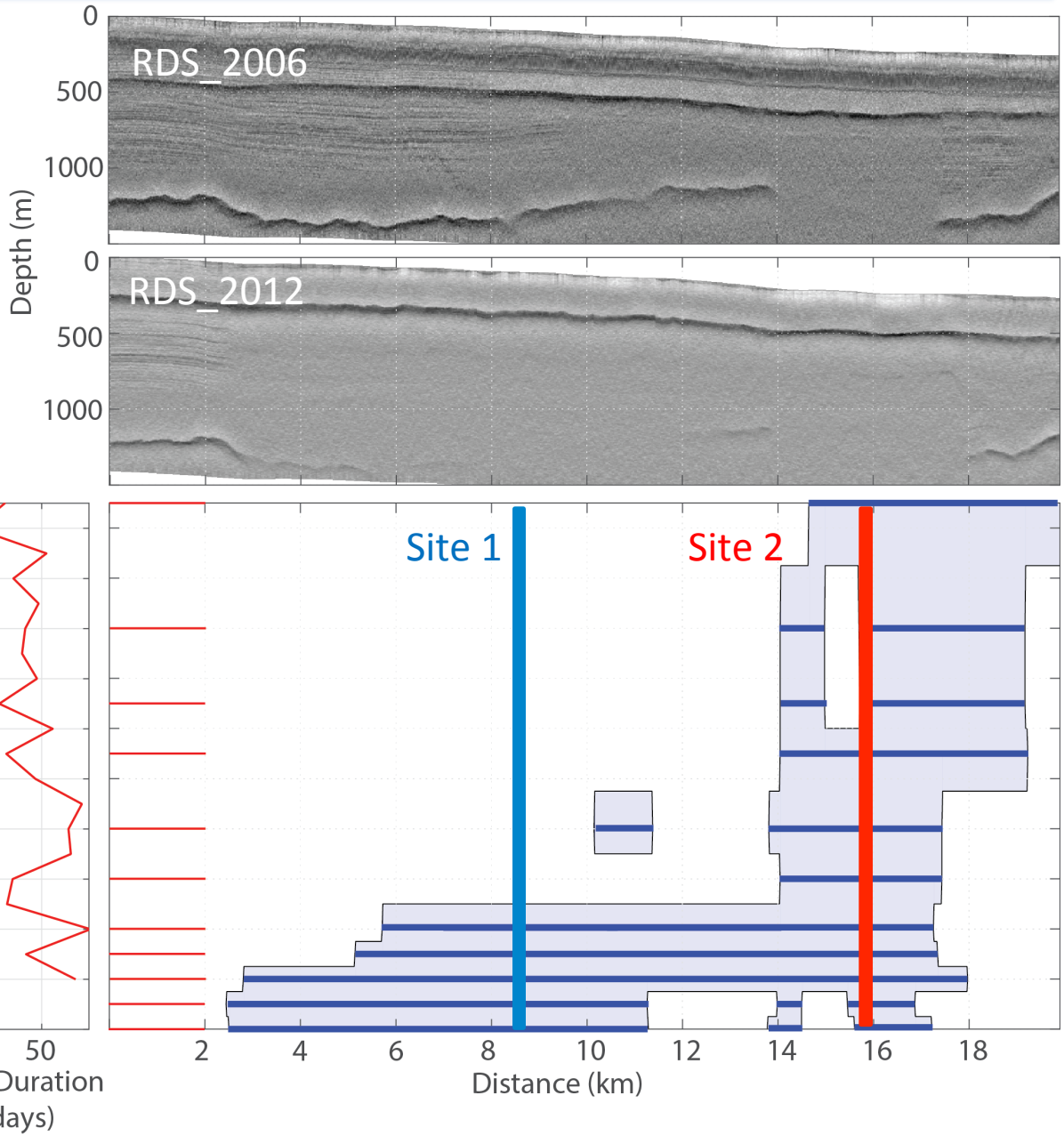


iWS from Univ. Utrecht

Firn aquifer progression:

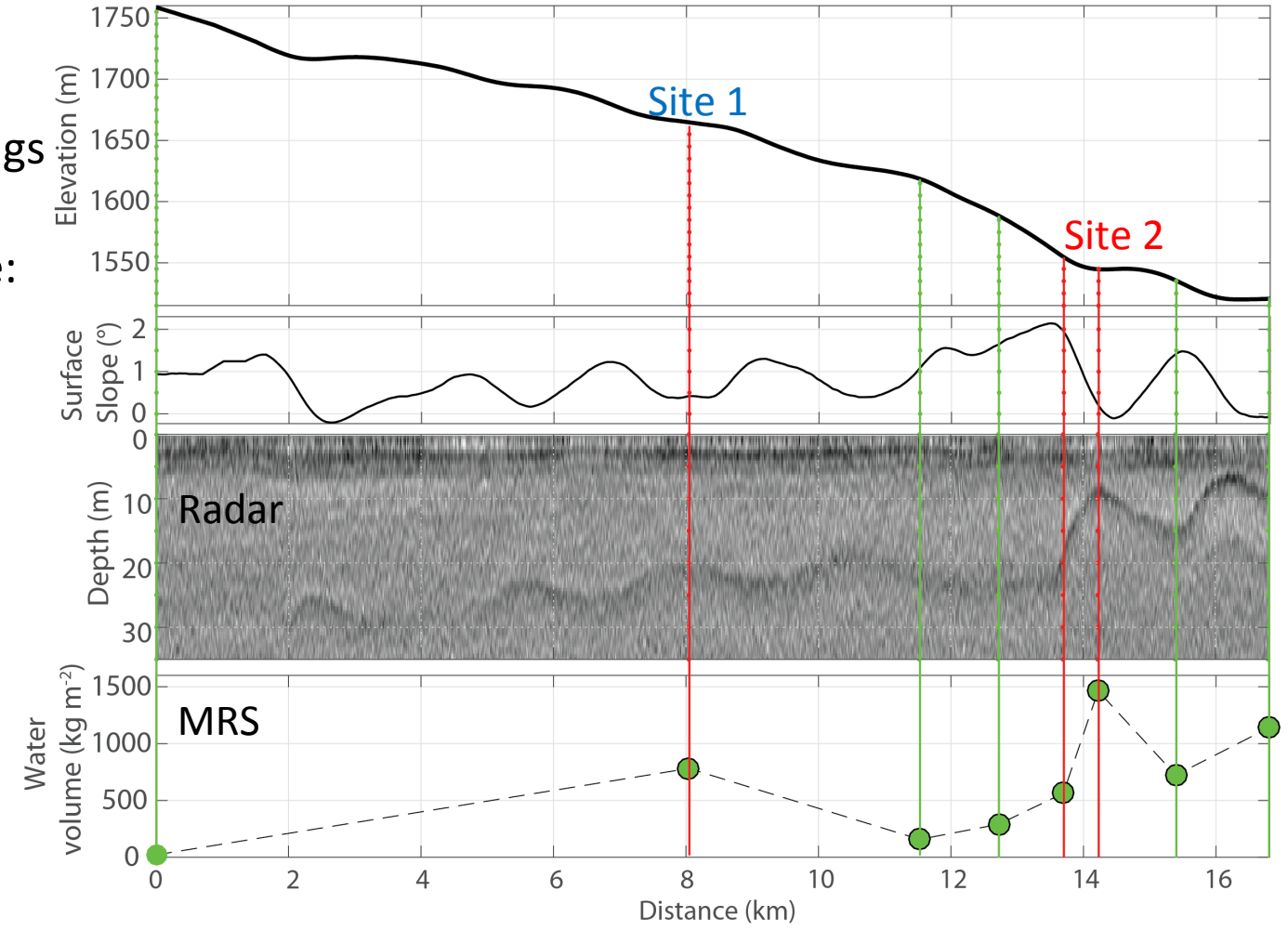
- Aquifer extends to higher elevations past spring 2008
- Small drainage (2-3 km) observed prior to spring 2013
- Aquifer progression is related to surface melt
- Younger aquifer at Site 1 compared to Site 2

Melt duration (*Mote 2014*)



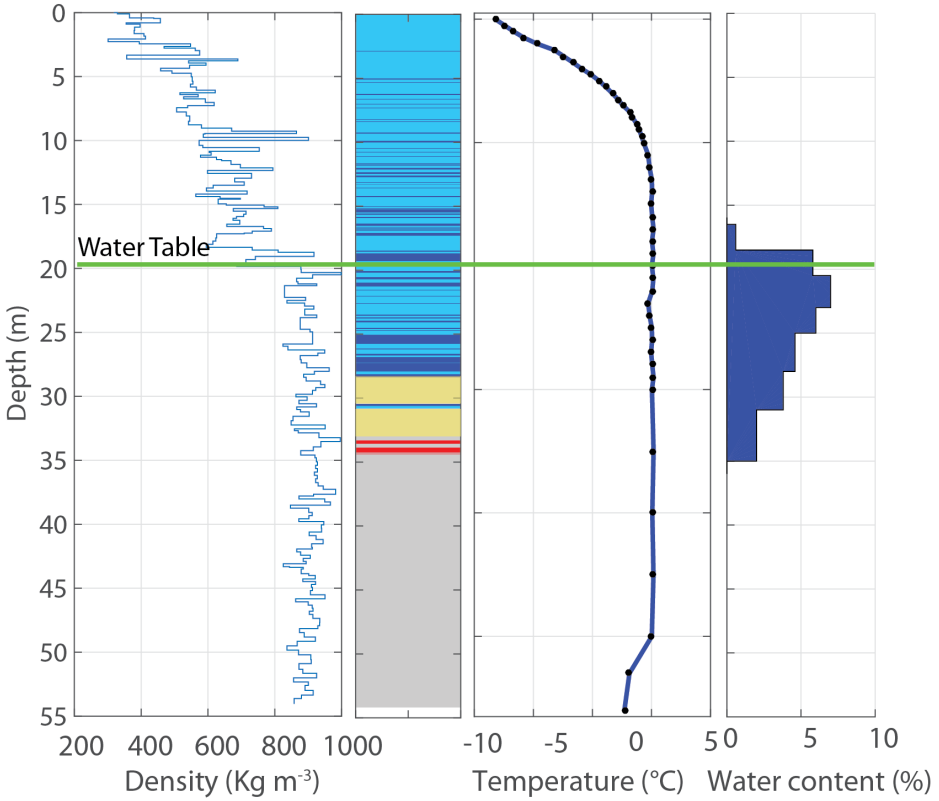
Water volume variations across a 16-km transect:

- 8 magnetic resonance soundings
- MRS water volume: 200 to 1500 kg m^{-2}
- Water volume higher in local depression (slope minima)
- Radar depth to water alone is not sufficient to infer volume

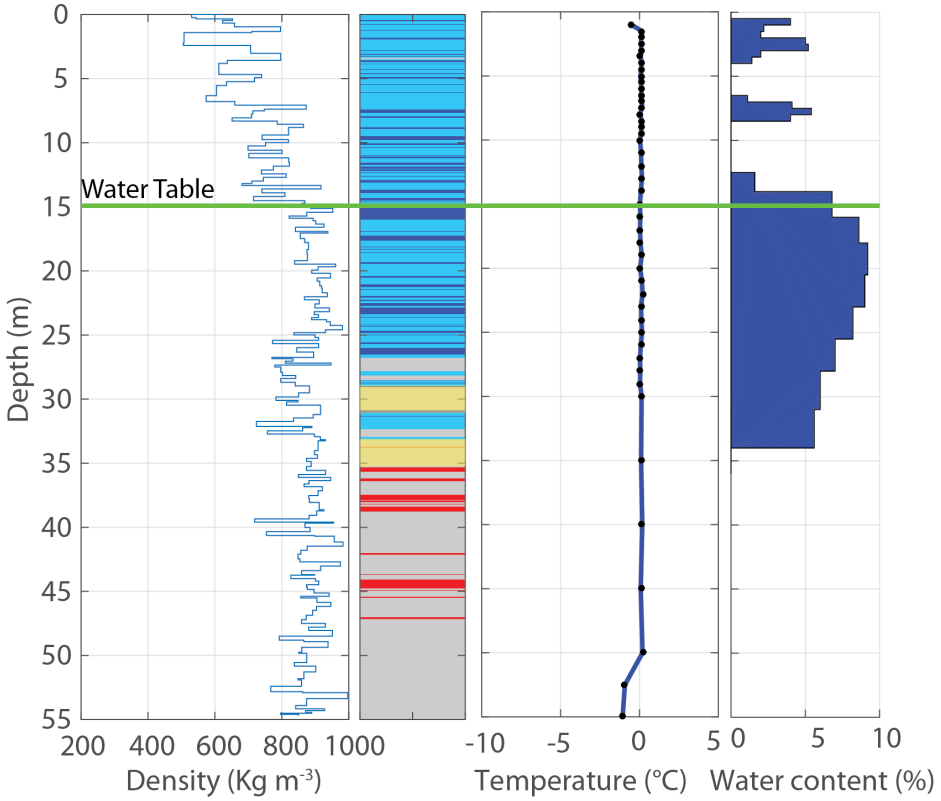


Firn-aquifer vertical structure:

Site 1 – April 2015



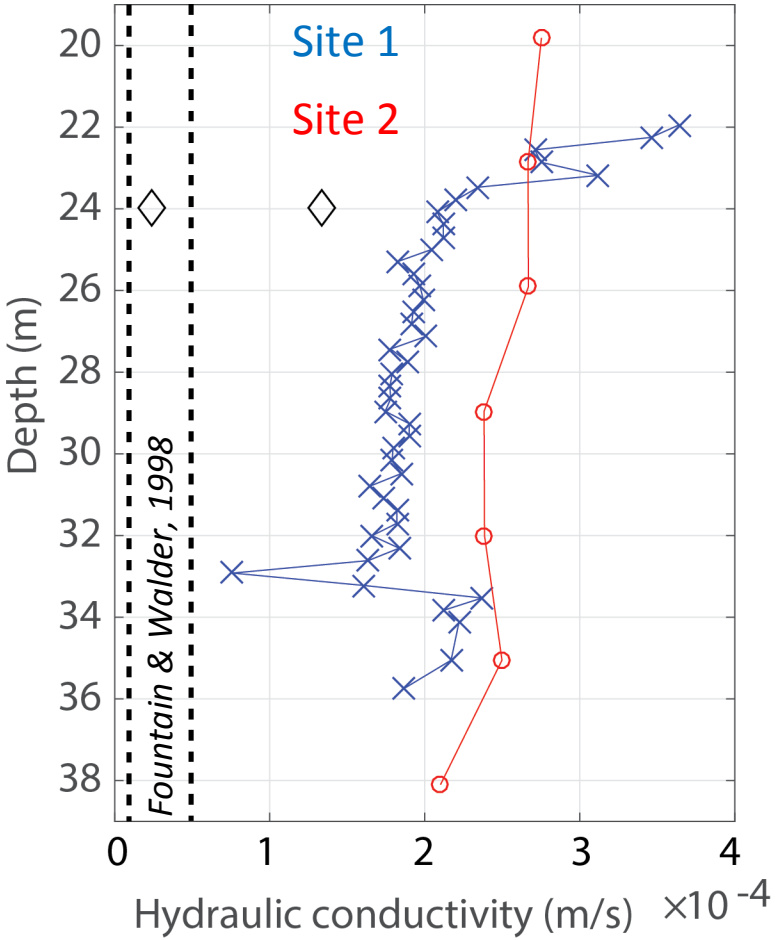
Site 2 – August 2015



- Progressive firn/ice transition at similar depths
- Past aquifer imprints as clear-ice layers
- Temperate to colder ice transition at ~ 50 m

Stratigraphy:
Firn – ice layers – clear ice
bubbly ice – Transition

Firn-aquifer hydraulic conductivities:



Initial hydrology results:

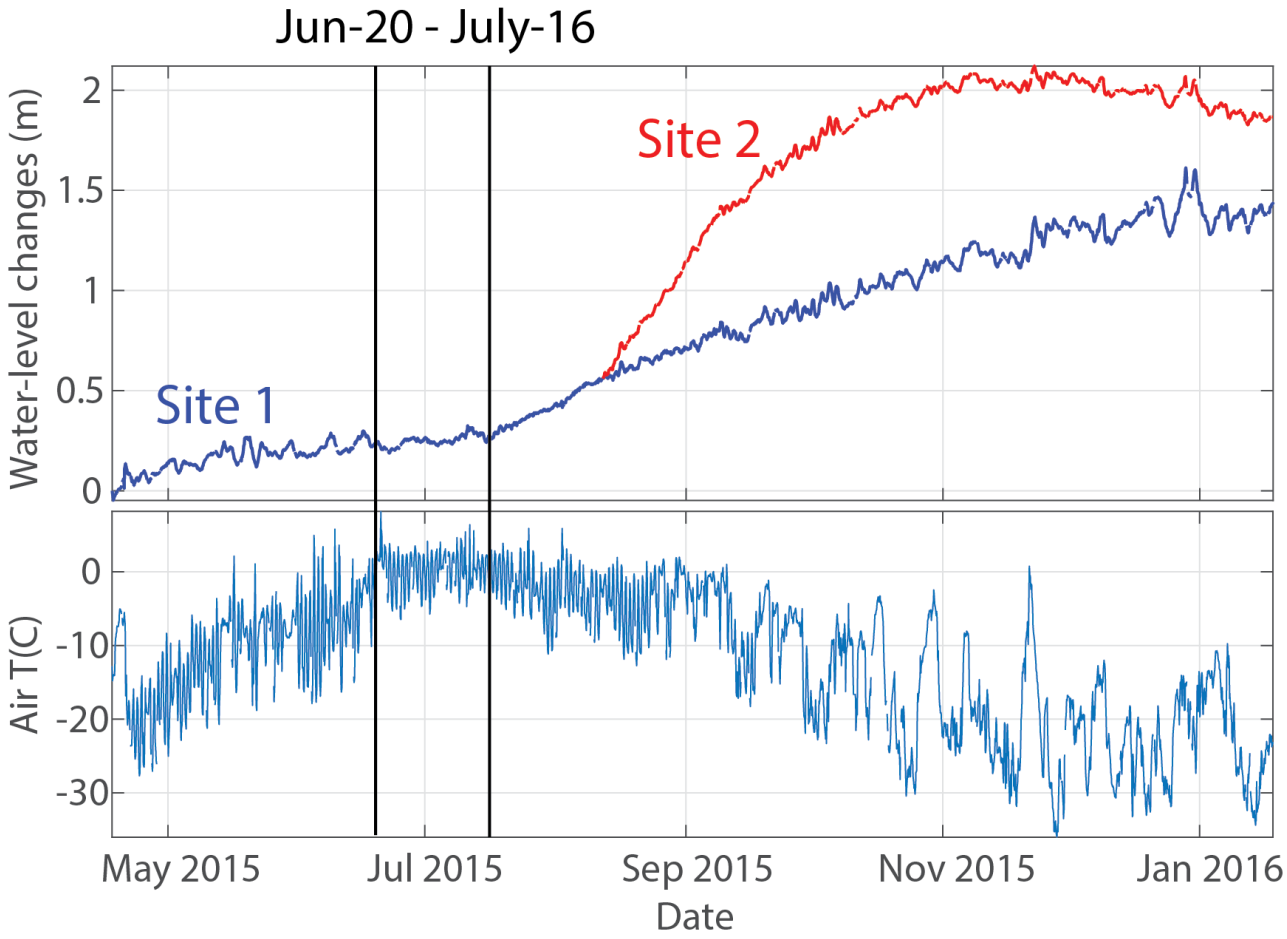
- High hydraulic conductivities

- Water will be replaced in the aquifer between 2-20 years

- CFCs indicate a rapid recharge (vertical percolation rates)

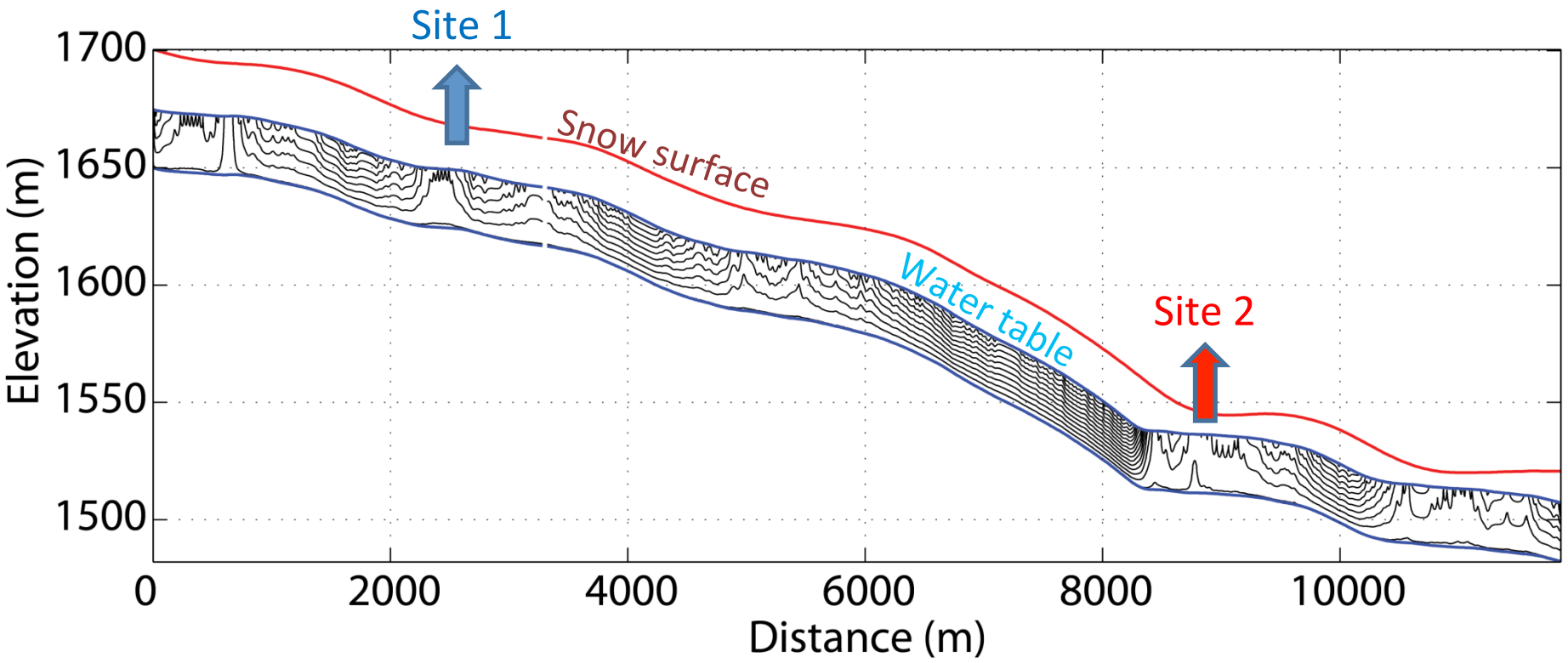
- Tritium shows age younger than 60 years

Water-level changes since April 2015:



- 1 month to bring water to the water table
- Water-level increase continues after surface melt shutdown

Agreement with a flowline simulation at steady state:



- Both sites located in local discharge areas

Main findings:

- Firn aquifer inferred since 1993, expand upstream after 2008
- Significant water volume variability (200-1500 kg m^{-2}) over 16 km
- Water residence time: 2-20 years
- Lateral flow observed within the aquifer through the fall/winter

Future work:

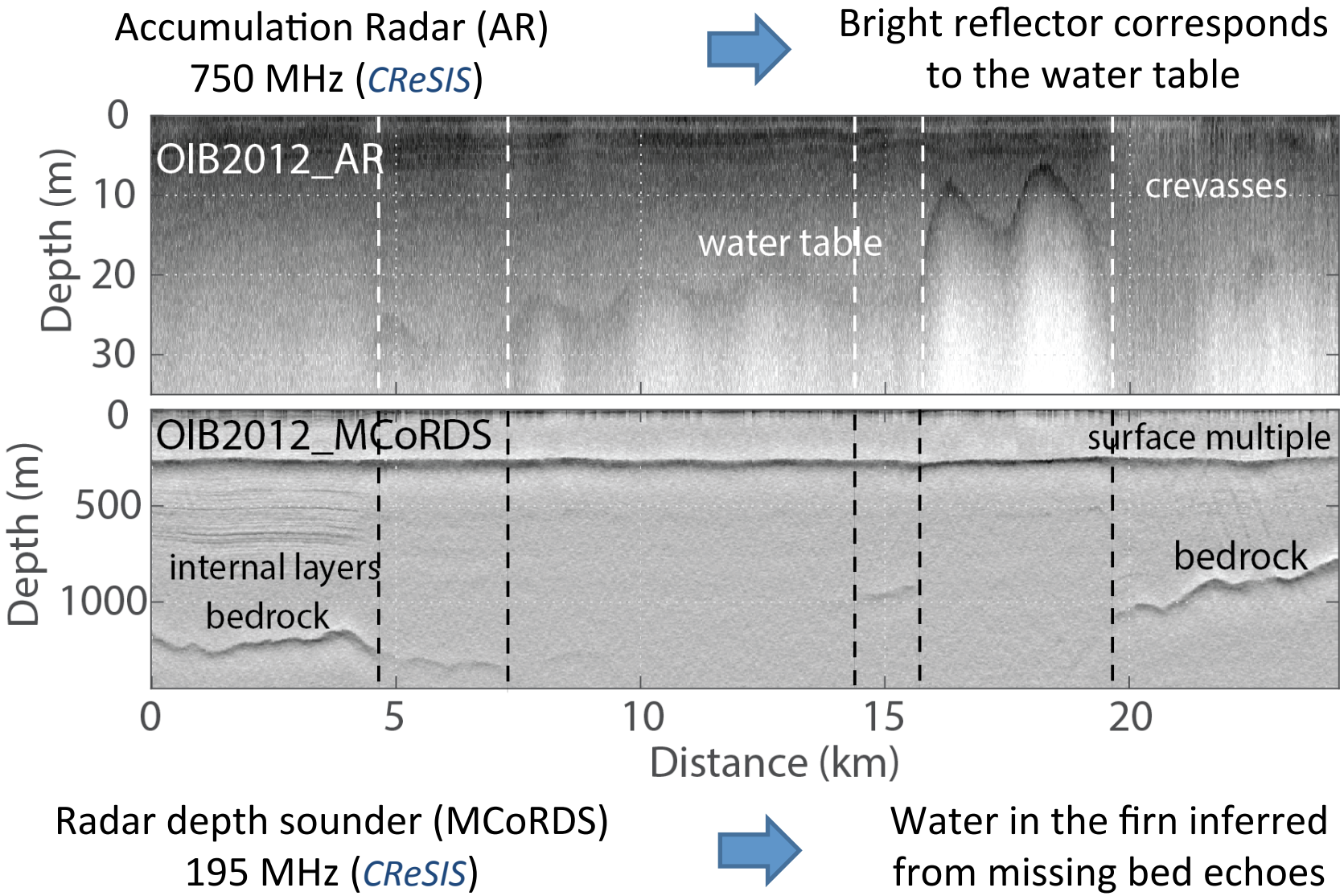
- Fieldwork during summer 2016
- Simulate aquifer interannual changes, lateral water flow and discharge
- Characterize connections to englacial hydrology

Thanks for your attention!

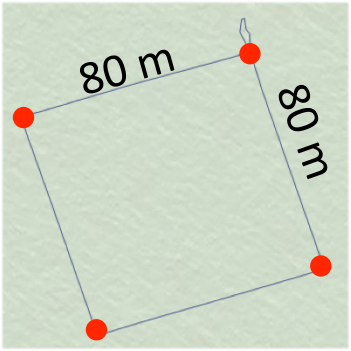
Funding:

Field support:

Radars and GPS:


Accumulation Radar (AR)
750 MHz (CReSIS)
Bright reflector corresponds to the water table
OIB2012_AR
water table
crevasses
Depth (m)
0
10
20
30
OIB2012_MCoRDS
surface multiple
internal layers
bedrock
bedrock
Depth (m)
0
500
1000
0
5
10
15
20
Distance (km)
Radar depth sounder (MCoRDS)
195 MHz (CReSIS)
Water in the firn inferred from missing bed echoes

- Magnetic resonance soundings (MRS) (LTHE, Grenoble)



Worldview image (DigitalGlobe©)

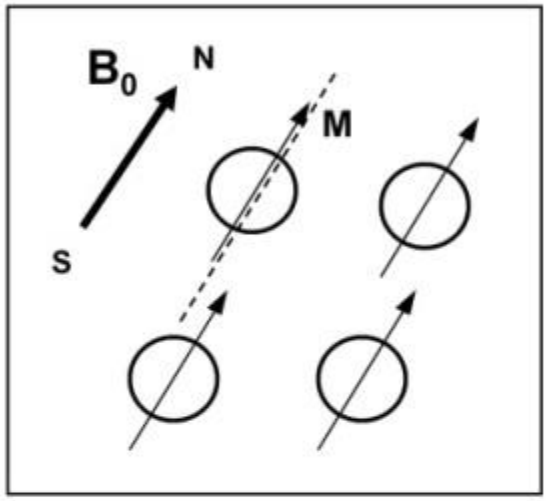
Photo: L. Montgomery

Methods:

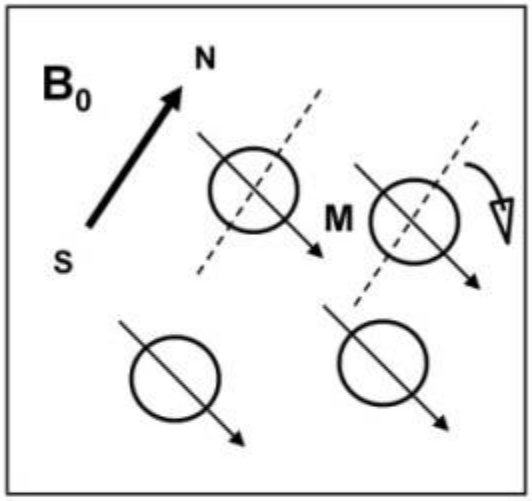
- Loop = transmitting / receiving antenna
- Pulse of alternating current
- Record magnetic resonance response

Typical phases of a magnetic resonance experiment

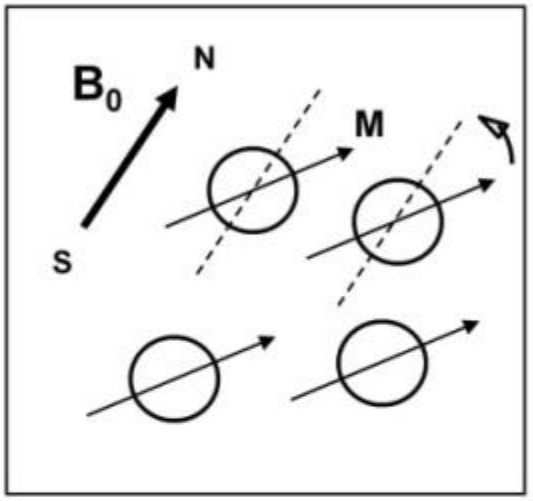
a) *Undisturbed state*



b) *Pulse transmission*

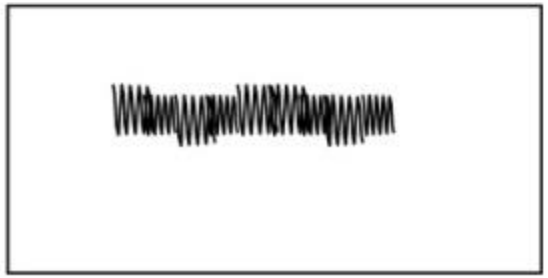


c) *Signal measurement*

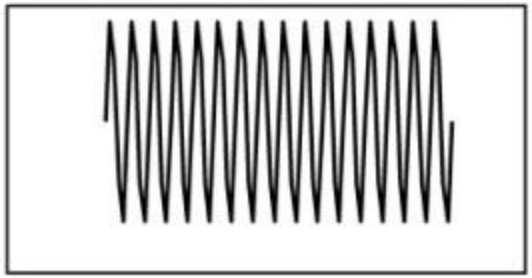


$\mathbf{B_0}$ – static magnetic field; $\mathbf{M}$ – nucleus magnetic moment

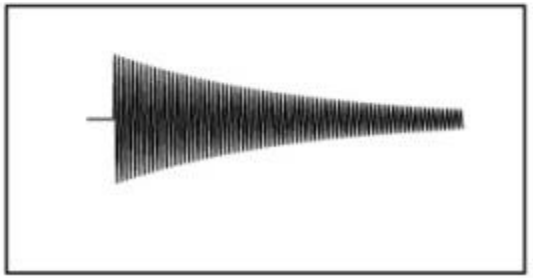
Corresponding magnetic resonance measurement



Ambient electromagnetic noise



Pulse of oscillating current



Received signal